

## LA-UR-21-30910

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Title: Physics Division Strategic Plan - Science Drivers

Author(s): Pietrass, Tanja

Intended for: Web

Issued: 2021-11-02

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# Physics Division Strategic Plan

## **Science Drivers**

Oct. 29, 2021

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## Contributors

### Foundations of the Universe

Keith Rielage, management lead  
Andrea Albert  
Aaron Couture  
Takeyasu Ito  
Ming Liu  
Fesseha Mariam  
Ralph Massarczyk  
Christopher O'Shaugnessy  
William Louis

### Measurement Advances

Shea Mosby, management lead  
Tiffany Desjardins  
Xuan Li  
John Ullmann  
Zhehui (Jeph) Wang  
Glen Wurden

### Weapons Regimes

Steven Batha, technical co-lead  
Maria Rightley, management lead  
Benjamin Tobias, technical co-lead  
Jonathan Ben-Benjamin  
Melynda Brooks  
William Buttler  
John Charonko  
Devin Connolly  
Dana Duke  
Kirk Flippo  
Matthew Freeman  
Mike Furlanetto  
Verena Geppert-Kleinrath  
Michael Ham  
Thomas Hartsfield  
Scott Hsu  
Anna Llobet  
Eric Loomis  
Yong Ho Kim  
Marc Klasky  
Frank Merrill  
Elizabeth Merritt  
Jacqueline Mirabal-Martinez  
David Montgomery  
Russ Olson  
Katherine Prestridge  
Jeph Wang  
Patrick Younk

## Executive Summary

The Physics Division Science Drivers articulate the overarching scientific objectives that we seek to address and that form the lifeblood of our Division. While many physics subfields are represented in the Physics Division's scientific portfolio, we strive to maintain or achieve excellence and international leadership in only a few areas. While diversity of science and engineering efforts is strongly supported and provides the fertile soil for innovation, there are dominating areas in which we must excel to accomplish our mission that is stated as: "We design, execute and analyze experiments that challenge, improve and validate our understanding of fundamental physics underpinning LANL's national security mission."

Our three priority areas are defined by two scientific questions that we strive to answer:

- 1. How do we discover the fundamental foundations of the Universe and explain unknown physical phenomena?**
- 2. How do we create, diagnose, and understand weapons-relevant experiments and physical regimes?**

The third priority area is focused on the primary tool kit employed by Physics Division to answer these questions. This area comprises both the Physics Division's legacy and predominant strength:

### **3. Advancing Measurements to Enable Predictive Science and Discovery**

This priority area is embodied in our vision ("Leaders in experimental physics serving the national interest") and mission, following our motto: "Experiendo cognoscitur" (Knowledge through Experiment).

In the following, the three areas are summarized. For full detail, please refer to the full descriptions available on our website

(<https://int.lanl.gov/org/ddste/aldds/physics/index.shtml>). The first priority area:

- 1. How do we discover the fundamental foundations of the Universe and explain unknown physical phenomena?**

is comprised of five sub-areas:

- **Why is there more matter than antimatter in the Universe?**
- **What is the origin of cosmic rays?**
- **What is the nature of dark matter?**
- **What are the portals to the dark sector?**
- **How do we predict nuclear fission?**

This priority area lies at the heart of the philosophical question of why we exist. It explores the foundations of our Universe – its origin and early evolution that left signatures behind for us to explore. One such signature is the asymmetry between matter and antimatter. Certain conditions need to exist to explain this imbalance, among them charge conjugation-parity

violation that can be explored by measuring the electric dipole moment of fundamental particles; neutrino oscillations in neutrinos and antineutrinos that occur when a neutrino travels a set distance; or the Majorana nature (a particle is its own antiparticle) of neutrinos.

The study of highly energetic (TeV) cosmic rays may also constrain the existence of dark matter, and the attenuation of cosmic rays through interactions with the extragalactic background light may indicate the existence of axions, a possible component of cold dark matter. Exploration of the dark sector, consisting of dark energy and dark matter, requires portals between the Standard Model (SM) and the dark sector, such as the neutrino portal. Proving the existence of sterile neutrinos would provide a portal for SM neutrinos to interact with dark matter via dark sector force mediators. LANL scientists have been leaders in large international collaborations (nEDM, DUNE, MAJORANA/LEGEND, HAWC, SpinQuest, DarkQuest, MiniBooNe) as well as in in-house laboratory-scale experiments (CAPTAIN MILLS, nEDM) and component development and testing for large collaborations (DUNE, LEGEND) to contribute to answering these daunting questions.

Understanding fission probabilities, the likelihood of a nucleus to disintegrate either spontaneously or following excitation, also lies at the heart of the foundations of the structure of our universe. In particular, we are interested in such events in neutron-rich environments with the ultimate goal of predicting them from first-principles, a goal that is only achievable with accurate and precise data sets describing the complex network of nuclear reactions. Such studies are not only relevant for understanding neutron star mergers and core collapse supernovae, but also for predicting the performance of nuclear weapons.

The second priority question is targeted at the latter, nuclear weapons performance:

## **2. How do we create, diagnose, and understand weapons-relevant experiments and physical regimes?**

and comprises five main areas:

- **Nuclear, Atomic, and Material Properties**
- **High Energy Density Regime and Thermonuclear Burn**
- **Hydrodynamic Experiments**
- **Archiving and Reanalysis of Historical Data**
- **Direct Certification Support**

Properties intrinsic to an element or compound are important to LANL in order to simulate the response of a system to internal and external forces. In order to overcome experimental limitations, theories and models currently fill such measurement gaps. The Physics Division strives to fill these gaps experimentally and by providing data that allow to discriminate among models in the areas of opacities, equations of state, nuclear cross sections, material strength, and the response of materials to dynamic loading.

We strive to achieve extreme conditions - the High Energy Density (HED) physics regime is one where radiation begins to play a major role and thermonuclear (TN) burning of fusion fuel is possible. Materials are usually in the plasma state and behave differently than in other regimes.

Such “hot physics” conditions place difficult constraints on our integrated codes and underlying models. Hydrodynamic experiments in both the low- and high-energy density regimes are used to develop and calibrate models, validate scaling arguments, and provide data for refinement of mix and hydrodynamic models. A particular area of interest is non-equilibrium flows that we pursue with both laboratory-scale and integrated experiments.

A critical component of this work is curating and analyzing legacy data that were collected in underground tests (UGT) in the context of uncertainty quantification. This not only allows for these data to be accessed via our Common Modelling Framework (CMF) but also reveals gaps in former tests providing the impetus for the design of new laboratory-scale or integrated experiments. We see the latter, support of direct certification, as an area of growth for Physics Division.

The third priority area:

### **3. Advancing Measurements to Enable Predictive Science and Discovery**

delivers the tool kit for both priority areas and constitutes the core of Physics Division’s mission and is organized in four areas of application:

- **Low-Energy Nuclear Physics**
- **Scaling Studies**
- **Inertial Confinement Fusion and Magneto-inertial Fusion Experiments (ICF/MFE)**
- **Quantum Chromodynamics (QCD)**

As laid out above, predictive science and discovery science are driving the frontiers in measurements in the Physics Division. They constantly demand higher spatial, higher temporal, and higher spectral resolution; higher data throughput; and higher sensitivity.

While many of our advances rely on the use of facilities that can be readily measured in higher luminosity, flux intensity or repetition rate, many of the data generation and collection instruments were developed decades ago.

In the area of low-energy physics, we focus on neutron-induced reactions both in stable and unstable radioactive targets, and continued advances in our detectors are critical to the success. Scaling studies strive to investigate how the results from small-scale experiments scale to integrated experiments in extreme conditions. While existing hard-ware displays impressive spatio-temporal metrics in the low-energy regime, there are large gaps in detector performance and characteristics in the high-energy regime and the extremes of temperature and pressure. In the ICF/MFE regime, we are replicating such conditions at smaller length scales with unique drivers that do not require the rigor of nuclear facilities for their operations. In the area of high-energy and particle physics, Quantum Chromodynamics, the theory describing the behavior of quarks and gluons as the constituents of elemental particles, depends on large facility experiments to generate data to further our fundamental understanding of matter and its interactions. The energy regimes of such experiments are relevant to our foundational physics of the universe questions with significance also to the applied LANL missions.

In summary, our Science Drivers lay out the areas of physics in which we want to attain or maintain international leadership. In essence, they provide the answer to “what” we do and “why”. The “how” is captured in our Strategy Articulation Map and the more detailed descriptions of our critical success factors captured in our Strategic Plan.

## How do we discover the fundamental foundations of the Universe and explain unknown physical phenomena?

To help direct the scientific strategy around this question, five focus questions were developed and short white papers on each were developed. These papers that follow present the scientific and technical context of the focus area, look at who is leading the area right now, examine why it is important that LANL leads in this area, and what is needed for this opportunity or to continue to keep leadership in this area.

The five focus questions are:

1. **Why is there more matter than antimatter in the Universe?**
2. **What is the origin of cosmic rays?**
3. **What is the nature of dark matter?**
4. **What are the portals to the dark sector?**
5. **How do we predict nuclear fission?**

### **FOCUS QUESTION: WHY IS THERE MORE MATTER THAN ANTIMATTER IN THE UNIVERSE?**

#### *Scientific and technical context*

It is generally accepted that there are three “Sakharov” conditions necessary to generate the baryon asymmetry that we currently observe in the universe. These are 1) Violation of baryon number conservation; 2) Violation of C-symmetry and CP-symmetry conservations; 3) A departure from thermal equilibrium.

The breadth of these conditions motivates a range of experiments and theories that seek to address them. With the exception of sphaleron processes that have been predicted but not experimentally observed, all standard model interactions conserve baryon number. The sphaleron processes, which are anticipated to be efficient at high temperatures and very inefficient in normal laboratory settings, would allow for electroweak baryogenesis and leptogenesis processes to generate the baryon asymmetry. The standard model sources of CP violation that have been observed are thus far rather weak, so there must be a stronger source of CP-violation if electroweak baryogenesis or leptogenesis processes can describe the asymmetry.

Electric dipole moments (EDM) of fundamental particles, neutrons, electrons and certain atoms, are sensitive probes of new sources of CP-violation. Within the standard model (SM), in the electroweak sector CP symmetry is broken by the complex phase ( $\delta_{KM}$ ) in the CKM quark mixing matrix. Therefore, the CP violation only occurs in quark flavor changing processes to the lowest order. Consequently, the EDM due to this SM source of CP violation is small. However, most extensions of the SM naturally produce larger EDMs because of additional CP violating phases associated with additional particles introduced in the model. Thus, EDM provides a sensitive probe of new sources of CP violation with negligible background from the SM processes.

As an example, the standard model predicts a neutron electric dipole moment (nEDM) of the order of  $10^{-32}$  e-cm while the current experimental upper limit is  $1.8 \times 10^{-26}$  e-cm (90% C.L.). nEDM probes mass scales up to the  $10^3$  TeV, beyond the reach of collider searches. Discovery of an nEDM that is much larger than the standard model prediction probes new interactions in mass scales that are unattainable at current particle colliders and could be a significant source of CP-violation that would allow electroweak baryogenesis to describe the baryon asymmetry. Another method is to measure CP violation in neutrinos after traversing a set distance and looking for differences in oscillations in neutrinos and antineutrinos. The Deep Underground Neutrino Experiment (DUNE) is currently being developed to study this difference.

From all the elementary particles neutrinos have not yet revealed their complete nature. The very light mass gave a hint that not the traditional mass creation through the Higgs coupling is present. If they are their own antiparticles, so-called Majorana particles, mass can be generated via the interaction with its own antiparticle. The Majorana nature also would solve a number of other Sakharov conditions. It allows for a CP-violating phase in the neutrino Majorana mass term that can generate a lepton asymmetry. In the lepton-driven leptogenesis this asymmetry can contribute to baryon asymmetry through the coupling of the leptons to other standard model processes.

One way to observe the particle-antiparticle nature of the neutrino is neutrinoless double-beta decay. It is observable in nuclei where single beta-decay is energetically forbidden because the daughter nuclei are more massive than the parent. However, a double beta-decay is allowed in which two neutrons are converted to two protons simultaneously and emit two electrons and two anti-neutrinos. This second order weak process with half lives of up to  $10^{21}$  years has been observed and is studied since. It is an unusual test bed for nuclear and particle theory, from particle couplings to nuclear matrix elements. If in addition, the neutrino is a Majorana particle it will sometimes emit only two electrons and no neutrinos. The signature for this is a peak in the electron energy spectrum at the Q-value for the decay. Hence, and observation of such a peak would directly show lepton-violation processes do exist.

*Who is leading this area right now?*

The current upper limit of the nEDM,  $1.8 \times 10^{-26}$  e-cm (90% C.L.), is provided by an experiment performed at Paul Scherrer Institute (PSI) in Switzerland.

There is a strong worldwide competition for reaching the sensitivity in the range of  $10^{-27}$  e-cm (or in some cases in the range of  $10^{-28}$  e-cm ) to set the next upper bound or discover a non-zero nEDM. These efforts include: n2EDM at PSI, PanEDM at Institut Laue Langevin in France, TUCAN at TRIUMF in Canada, nEDM@SNS at Oak Ridge National Laboratory in US, and LANL nEDM at LANL. Among these, three experiments n2EDM, PanEDM, and LANL nEDM are in the position to reach the sensitivity of  $10^{-27}$  e-cm in the next few years. TUCAN is still developing their UCN source. SNS nEDM, which LANL P-division is playing a major role in, aims to reach a sensitivity of  $10^{-28}$  e-cm with a novel method based on a large LHe cryogenic system..

DUNE is a flagship project for the DOE Office of Science and builds on a legacy of many large scale neutrino experiments. It involves a large international collaboration and is currently the leading world-wide effort in this area.

After its starts in the 80's neutrinoless double beta decay experiments have been evolved to experiments on the scale of about tens of kilograms. Using enriched materials and run-times of one or two years, they are able to exclude half-lives of  $10^{26}$  years. Xenon- and germanium-based experiments lead the field. While Xenon experiments were able to achieve these limits with large mass. Germanium experiments use the features of germanium detectors, and achieved the worlds-best energy resolution, that combined with ultra-clean environments and active vetoing reached the same limits with smaller exposures. Next generation collaboration efforts are on its way, like the LEGEND experiment that combined the worldwide knowledge of experts from the current germanium experiments MAJORANA and GERDA. The goal of all ton-scale efforts is to cover  $10^{28}$  years and more. Here, it is expected that the inverted neutrino mass scale ordering has to show the nature of neutrinoless double-beta decay. If not observed, large portions of the theories are excluded and the question of the mass ordering are solved.

*Why is it important the Physics Division leads LANL in this area?*

The SNS nEDM experiment started at LANL Physics Division as an LDRD project in the late 1990s to early 2000s. Although the project is now based at ORNL (as the experiment will run at the SNS), LANL P-division scientists and engineers play a major role in technical and engineering development of the experiment. In fact, in the development of this technically challenging experiment, it utilizes many of our unique capabilities, including: large scale and sub-kelvin helium cryogenics, precision magnetometry and high voltage. In addition, the LANL Ultracold Neutron (UCN) Source, the only operating UCN source in North America that is providing UCN to physics experiments, has been playing an important role in the development of the SNS nEDM experiment.

Furthermore, the LANL UCN source is one of the most intense sources of UCN in the world, and has enabled the LANL nEDM experiment. This experiment that is based on the traditional room temperature Ramsey method will be able to produce competitive physics results during the development and construction of the challenging SNS nEDM experiment. It will also provide a platform to train the next generation physicists that will carry out the execution of the SNS nEDM experiment.

These efforts (LANL nEDM and R&D for SNS nEDM) heavily leverage resources available in TA-53. For example, the LANL UCN source is based on spallation neutrons produced using the proton beam from the LANSCE accelerator. At the same time they benefit LANL by attracting external talents to LANL.

Physics division should lead the efforts in neutrinoless double-beta decay, especially in LEGEND, due to the cutting edge detector and analysis methods involved. We already have leadership in field like enriched materials procurement, clean-room sites, and calibration systems. Our efforts allow us to lead a wide range of experiments with different collaborators. We lead a liquid Argon test stand in collaboration with UNM, and have successfully competed with other institution e.g. USD for grants to work with us. The calibration efforts lead to extra DOE funding where we designed, produced, and tested in-house in collaboration with Sigma and Chemistry new radioactive sources for LEGEND-200. While these groups bring specific expertise to the table our physics interest was the driver to combine all of these teams. Low-background counting in general has proven to be a very fruitful collaboration with C-NR group. While their

focus lies on the day to day work running a large number of samples for various parties, they are interested in the specific knowledge people from the Physics Division gained while pushing the low background counting to its limits in double-beta decay. We bring a larger expertise to the table for R&D efforts that open-up new facilities like the TA-41 tunnel, hence improving existing systems and mission relevant-capabilities. Last but not least, the collaborative nature of the current and next generation experiments gives us access to an international, and also a very diverse pool of students and next generation physicists.

Participating in DUNE, a DOE flagship project, provides a valuable opportunity for LANL to make major contributions to the international high energy neutrino community and will serve as a training ground for the next generation of scientists. Physics Division is now playing a central role in several aspects of the experiment after a strategic hire in this area. This will ensure the continuation of the division's prominence in the field for some time to come.

*What do we need to focus on for this opportunity or to keep leadership?*

LANL has been one of the world leaders in the field of fundamental neutron physics, owing to our unique capabilities including the UCN source. The high cost of doing business at LANL has so far been offset by many advantages and unique capabilities. We are in a position to produce new results in the area of neutron EDM search in the near future. It is important to maintain and further grow all of our infrastructure, capabilities, and talented staffing in order to maintain our leadership.

As stated before, we already have leadership positions in current experiments and the next generation efforts. As stated in the DNP meeting in 2020 by DOE representative T. Hollman DOE will seek that multiple double beta decay experiments are built. Hence, germanium based experiments like LEGEND, will be an important driver in the whole NP community over the next decades. If we do not support the current efforts, especially by growing staffing, we will heavily compete on the leadership positions we have right now. Multiple, international groups e.g. from universities, often much larger in size, will try to replace parts of our bundled expertise, hence weakening our attractiveness for hiring future talents. While we are equipped reasonably with hardware and lab space, the double beta decay program would benefit from the division support of at least one or two more post-docs. Continuing support for our efforts in DUNE as it is developed, built and operated will be key for continued leadership in this area as well.

## **FOCUS QUESTION: WHAT IS THE ORIGIN OF COSMIC RAYS?**

### *Scientific and technical context:*

The birthplace and creation mechanism of cosmic rays is a current research area full of unanswered questions. We have identified several birthplaces like Pulsar Wind Nebulae (PWN), Supernova Remnants (SNR) and Core Collapse Supernova (CCSN). These have been studied over a broadband of wavelengths. Typically the cosmic ray acceleration models are divided into two groups: hadronic or leptonic where the particles accelerated are protons or electrons respectively. Further, both the progenitors to SNRs and the CCSN environments are active nucleosynthetic sites, which open the door to using observed nucleosynthetic yields as an multimessenger probe to understand the environment where the cosmic rays are generated.

This gives an additional handle into understanding the origin of the heavy elements while simultaneously furthering our understanding of the origins of cosmic rays.

### *Who is leading this area right now?*

The High Altitude Water Cherenkov (HAWC) Observatory is currently the most sensitive cosmic gamma-ray experiment above 10 TeV. Therefore it measures the highest energy range of the cosmic ray source spectra. LANL scientists are leaders in the HAWC Collaboration and have recently collaborated with LANL theorists to model positron emission from Geminga (a PWN) leading to a paper in Science. LANL collaborators in CCS, XCP, and T-2 are leading modelers of both the progenitor to the SNR as well as CCSN collapse, including both the hydrodynamic conditions as well as the nucleosynthesis networks. P-division staff provide critical tests of the nuclear reaction inputs needed to use these signatures through LANSCE and other facilities.

### *Why is it important the Physics Division leads LANL in this area?*

The fundamental physics challenges addressed in this science thrust are embedded throughout the Nuclear Particle Futures strategy document, in many ways defining why NPF is a unified pillar instead of simply co-located science thrusts. Modeling and understanding turbulence and mix are key research areas for the High Energy Density, Plasmas, and Fields thrust.

Determination of nuclear reaction rates with LANSCE and FRIB is a core capability for the Applied Nuclear Science and Engineering thrust. Multi-physics modeling, astrophysical observation, understanding transient phenomena, and multi-messenger astrophysics are all key constituents of NPF's Nuclear Physics, Astrophysics, and Cosmology thrust. Physics division is the key experimental core that both tests the models and theory and pushes these efforts forward as a capability that cannot be matched at a less diverse institution. Additionally, the HAWC energy range overlaps with IceCube's. IceCube is a cosmic neutrino experiment, allowing multi-messenger studies.

### *What do we need to focus on for this opportunity or to keep leadership?*

We need to continue fostering collaboration between the Physics Division and the modeling and simulation efforts in Theory Division, XCP and CCS. There is an opportunity to leverage existing investments in HAWC, at the cosmic ray detection side, and the nuclear reaction measurement capabilities together scientifically to allow a more comprehensive approach to the science question. Such cross-disciplinary efforts both strengthen the multi-messenger

science we perform and capitalize on LANL's strengths in addressing multi-physics challenges. We also need to keep a strong LANL presence within the HAWC Collaboration. We should also explore partnerships with IceCube scientists to perform multi-messenger analyses. Note IceCube is NSF funded.

## **FOCUS QUESTION: WHAT IS THE NATURE OF DARK MATTER?**

### *Scientific and technical context:*

Observational cosmic data overwhelmingly supports the idea of dark matter being the dominant gravitational force in the Universe. The leading theories predict that dark matter is a fundamental particle. This particle could interact with Standard model particles and produce detectable signatures. Such signatures include an excess of secondary particles from dark matter annihilation or decay in cosmic sources like the Galactic Center and dwarf galaxies. We could also see dark matter interact with the target material in terrestrial experiments.

Examples of these secondary particles are gamma rays, positrons, and neutrinos. This naturally leads to multi-messenger searches for dark matter by combining the data from various experiments like satellites like the Alpha Magnetic Spectrometer (AMS) and ground based experiments like the High Altitude Water Cherenkov (HAWC) Observatory. Additionally dark matter could interact in terrestrial detectors like CAPTAIN and DUNE, which use liquid argon.

These are passive detectors with a large amount of target material that the dark matter could interact with. The low-background nature of the double-beta decay experiments has also been demonstrated to set world leading limits on various dark matter candidates.

Currently no experiment has detected a definitive dark matter signal and stringent constraints have been placed on the size of dark matter's coupling to the Standard Model. However, several promising dark matter candidates still exist unconstrained. Therefore, next generation experiments and new experiments are needed to continue exploring the dark matter phase space. Examples of next generation experiments are the Southern Wide field Gamma-ray Observatory (SWGGO) and DUNE. Examples of new opportunities are Captain and table top experiments. While not their primary effort, the large investments made by the community in double-beta decay experiments justify a broad physics program. Next generation experiments that can keep up their current features of e.g. looking for DM are very attractive for the community on multiple levels. Another opportunity is to develop novel tabletop DM experiments that could eventually be scaled up to larger detectors and to utilize the facilities at LANSCE to constrain possible axion parameters.

### *Who is leading this area right now?*

Most experiments are represented by an international collaboration. For example, the HAWC Collaboration is composed of over 100 scientists from 30 institutions across the globe. LANL scientists have key leadership roles in HAWC, CAPTAIN, and DUNE dark matter programs. Future smaller scale experiments could only involve a small number of LANL scientists as opposed to being run by a large collaboration.

While part of larger collaboration, LANL scientists have used the data of the MAJORANA experiment to set leading limits on bosonic dark matter in the keV-range, on fractional charged particles, and solar axions. The extreme radiopurity of the experiment allowed it to set limits with tens of kilogram year exposure competing with experiments in the ton-scale range.

*Why is it important the Physics Division leads LANL in this area?*

Investigating the particle nature of dark matter is one of the five Science Drivers from the most recent P5 report, indicating it is a priority of the DOE Office of Science High-energy Physics division. Additionally, exploring fundamental physics is a main thrust in the NPF strategy, in which dark matter plays a key role. The Division also plays a lead role in the use of LANSCE and can utilize this unique facility as a potential source for low-energy dark matter searches.

DM and beyond standard model searches are supported by Theory Division. Over the last decade we have combined our efforts, where experimentalists and theory worked hand in hand to maximize the experimental data analysis. Physics Division should lead these efforts at LANL due to our connection to larger scale experiments. While table top experiments are a great R&D effort and will push the next generation efforts, leadership in the current ongoing efforts will position us to translate all this R&D in future leadership.

*What do we need to focus on for this opportunity or to keep leadership?*

To keep LANL scientists as leaders in the field, funding to work on existing experiments like HAWC and CAPTAIN is needed. Additionally, we need to establish a strong LANL presence in future experiments like SWGO and DUNE. LANL also should support now the development on the next generation double beta decay experiments, while they are in the design phase, in order to extend the richness of the physics and lead later analysis efforts.

There are novel ideas for smaller scale table top experiments that will need seed funding to make them competitive for future LDRD funding. Other divisions are pushing e.g., in the Quantum sensor range. We have to get funding to support staff and postdocs to collaborate with these groups to transfer these table-top concepts to large scale experiments. Finally, we need to continue fostering collaboration between the Physics and Theory divisions.

Furthermore we should intensify our efforts to make use of the knowledge existing at MST. The current approach of just increasing the experimental size will limit DM searches one day, especially when they hit the neutrino floor as a background. New materials and techniques outside the traditional field are needed for the future.

## **FOCUS QUESTION: WHAT ARE THE PORTALS TO THE DARK SECTOR?**

### *Scientific and technical context*

The dark sector consists of dark energy and dark matter, which account for 95% of the mass-energy of the universe. However, at present, the composition of dark energy and dark matter are unknown and represent, arguably, the most important questions in physics today. In order to begin to understand the dark sector, theorists have advocated the study of possible portals between the Standard Model and the dark sector. There are just three UV-complete relevant portals to a SM-neutral hidden sector: Vector portal (dark photon), Higgs Portal (dark Higgs) and Neutrino portal.

### *Who is leading this area right now?*

Portals to the dark sector are being vigorously studied by a plethora of national and international experiments. However, LANL is one of the leading institutions in the world. One of the most studied portals is the neutrino portal, where active neutrinos in the Standard Model can mix with sterile neutrinos that are part of the dark sector and where sterile neutrinos can interact with dark matter via new dark sector force mediators. Evidence for sterile neutrinos comes from the LSND and MiniBooNE neutrino experiments, which observe excesses of electron-neutrino events in muon-neutrino beams, and future accelerator, reactor, and radioactive-source experiments have the capability of proving the existence of sterile neutrinos and the neutrino portal to the dark sector. For the Dark photon and Dark Higgs search, LANL is a frontrunner leading the SpinQuest and DarkQuest program at Fermilab, using the high intensity 120GeV proton beam from the Main Injector to carry out the world's most sensitive search today in a wide uncharted and highly motivated kinetic region by trying to directly create and detect them in the laboratory.

### *Why is it important the Physics Division leads LANL in this area?*

LANL-led experiments have opened up the possibility of the Neutrino, Dark photon and Dark Higgs portals using hadron and neutrino beams at the High Intensity Frontier at the Fermilab, as well as the Neutrino beam at Lujan. These experiments are gaining considerable interest and have made LANL a world leader in dark sector search physics. The synergy between LANL-led dark sector search physics and DOE Office of Science programs, including HEP supported neutrino and NP supported QCD programs, positions LANL in leading this endeavor to discover new physics beyond the Standard Model.

### *What do we need to focus on for this opportunity or to keep leadership?*

The next generation of neutrino experiments at Fermilab, Lujan, and elsewhere have the capability of proving the existence of sterile neutrinos and the neutrino portal to the dark sector. Also, the 120 GeV high energy proton beam dump experiments at the Fermilab High Intensity Frontier Facility opens up a new opportunity now to directly search for dark photons and dark Higgs in a highly motivated mass region of 1 MeV to 10 GeV. By supporting these next generation experiments and by maintaining the close connections between Physics Division and Theory Division, LANL will remain as one of the world leaders in the study and understanding of the dark sector.

## FOCUS QUESTION: HOW DO WE PREDICT NUCLEAR FISSION?

### *Scientific and technical context:*

Nuclear fission is the process in which a heavy nucleus, either spontaneously or following excitation, breaks into two or more excited fragments, emitting photons and neutrons as part of the de-excitation process. Understanding fission probabilities, how and which fragments form in fission, and neutron production from the fission process are just a few of the fission properties that drive element synthesis in extreme, neutron-rich environments such as neutron star mergers and core collapse supernovae.

Prediction of fission is one of the most comprehensive tests of a truly predictive model of the forces that bind and control the atomic nucleus. While the process can be modeled phenomenologically, we are still decades away from first-principles treatment of fission.

Advances in mean-field theory are moving us closer to a predictive understanding, but require further experimental tests of the many fission observables.

### *Who is leading this area right now?*

Los Alamos National Laboratory has a long and storied history in the study of fission due to its critical coupling to understanding the performance of nuclear weapons. LANL's combination of nuclear theory to model and evaluate the fission process together with LANSCE capability for direct measurement of fission properties from cross sections, to gamma-ray outputs to neutron emission are unparalleled in the world.

### *Why is it important the Physics Division leads LANL in this area?*

Any foundation to a predictive model for fission will necessarily be grounded in experimental studies of the fission process. The LANSCE facility is without peer for direct investigation neutron-induced fission on long-lived isotopes. Physics division stewards nuclear science at the LANSCE, and these studies are critical to the simultaneous advances being made in Theory division. Further, as advanced radioactive beam facilities are coming online, allowing investigation of fission on more exotic species through non-neutron channels, Physics division enjoys, for the time being, a competitive advantage and insight into how to best advance fission physics at these facilities due to our long history and extensive history in studying fission.

### *What do we need to focus on for this opportunity or to keep leadership?*

In order to maintain our leadership in this discipline, we need to

- 1. Reinvest in our world-class accelerator and measurement capabilities for fission studies, in particular, on correlated fission output studies.**
- 2. Strengthen experimental/theoretical/simulation collaborations to propel the synergies that have made LANL the world-leader in fission studies**
- 3. Selectively engage with and lead fission studies at rare-isotope facilities to complement our direct measurement program and ensure that technological advances at external facilities do not cause us to squander our competitive advantage.**

## Advancing Measurements to Enable Predictive Science and Discovery

Measurements are essential to experimental science in general and Physics division in particular. On many occasions, however, more emphasis has been placed on facility investment over instrumentation development, a situation that could (if it hasn't already) hamper the full and effective utilization of the 'particle sources' (protons, neutrons, photons, a plasma, an implosion target, etc.). While advances in a modern facility can be readily measured in higher luminosity or flux intensity or rep rate, it may be surprising that many such state-of-the-art facilities are still relying on instruments that were developed decades ago to generate scientific data. 'Delivering particles or fluxes' is only a part of the story, however. Delivering scientific data is a higher-level goal which requires ideally, seamless integration of the sources with instruments and data methods (high-throughput high-rep rate facilities are facing the new bottleneck of data rate or bandwidth, for example) that optimize the data, and therefore the scientific, yield. It may be shown that the gains in data collection through better instrumentation and methods outweigh the investment to enable such a gain in the long run, since most facilities are designed to last many decades.

Predictive science and discovery science are two drivers of the frontiers in measurements in the Physics division. They constantly demand higher spatial, higher temporal, higher spectral resolution, higher data throughput (for predictive science such as weapon's applications and modeling), and/or higher sensitivity (for discovery science, such as rare events detection or weak interaction sensing in search for double beta decay or dark matter). In addition to optimize the existing methods and hardware, advancing measurement capabilities now see the emerging opportunities of new measurement principles such as quantum physics, or interdisciplinary approaches such as introduction of new materials or structures (as sensors) or new data processing techniques. We note a set of specific opportunities below:

### LOW-ENERGY NUCLEAR PHYSICS

Low-energy nuclear physics, and in particular neutron-induced reactions, has been studied at Los Alamos since the Manhattan Project. These reactions drive energy production, reaction "poisons", and diagnostic capabilities in nuclear explosives, but also in nuclear reactors and in stars, where the study of the synthesis of nuclei is a subject of great interest. Despite being studied for 75 years, there are many gaps in our knowledge, and for many reactions it is difficult to make accurate theoretical predictions. Precise experimental measurements are still needed for all applications, and LANL currently is a global leader in nuclear reaction physics in large part due to the unique capabilities maintained at the Los Alamos Neutron Science Center (LANSCE).

There are two general opportunities for LANL to strengthen its leadership in nuclear reaction physics. The first is the broad field of neutron-induced reactions, where the LANL Weapons Neutron Research (WNR) and Lujan facilities continue to be world centers for basic and applied experimental research. Much of this work is supported by the weapons program, but the results have wide utility in applications such as reactor physics, criticality safety, and nuclear

astrophysics. Ongoing investments in the Lujan Center spallation target will give us new access to the key keV to MeV region where existing facility limitations are hindering progress. Investment in detector systems and science programs to exploit the facility could deliver the next generation of neutron capture and scattering physics to programs spanning NNSA's Office of Experimental Sciences (OES), Global Security, DOE's Nuclear Criticality Safety Program, the Office of Science [1,2].

The second area is in the study of neutron-induced reactions on unstable (radioactive) targets. This capability is being proposed as a possible future application for major facilities such as the new Facility for Radioactive Ion Beams (FRIB), but LANSCE has the capability today of producing radioactive targets at the Isotope Production Facility (IPF), and of studying highly radioactive targets at the WNR and Lujan target areas. LANSCE offers the ability to *directly* study the quantities of interest, whereas proposed work at FRIB will pursue indirect techniques which do not completely bound the physics problem. Possible future LANSCE upgrades, such as the restoration of high-current 800 MeV proton beams, could open up the capability for producing many more unstable nuclides. Understanding reactions on unstable nuclei is an exciting direction for the applied programs, nuclear astrophysics, and the basic physics of nuclei - essentially no experimental data exist so the discovery potential is tremendous. As a first step, programmatically stabilizing the Low-Energy N, Z (LENZ), Device for Indirect Capture Measurements on Radionuclides (DICER), and Detector for Advanced Neutron Capture Experiments (DANCE) projects would ensure that this physics opportunity is realized. Longer term, collaboration with IPF and the LANSCE Facility Director to gain capability through a radionuclide separator and WNR target upgrade would ensure this nascent program's vitality. Ultimately, a LANSCE-based Neutron Target Facility could complete our study of this field [1-3].

## SCALING STUDIES

Many of our research codes rely on the information obtained from very basic, simple experiments to validate them, from Equation of State (EOS) values, to dynamic flow behavior. However, it's unknown if the results from these small simple experiments scale to larger experiment and applications. Physics division is actively part of the verification and validation of our scientific codes at the laboratory. One of the difficulties in this process is that physics of interest to the laboratory spans a wide arrange of spatial and temporal scales, as well a wide range of energy scales, from simple gases to high density plasmas. Diagnostics low-energy regimes tend to have advanced spatiotemporal resolve diagnostics, while the diagnostics for high energy regimes remain far behind due to the difficulty of measurements. Our advanced simulation and research codes have to rely on the assumption that physics scales from these low-energy density regimes to high-density regimes. Recent experiments in Physics division have been focused on understanding if this assumption is valid, and where it breaks down.

One example of this issue is the recent opacity measurements from Sandia, which found that at a certain density and temperature threshold the opacity measurements no longer match theoretical models. One of the difficulties of these experiments is the (limitation of) instrumentation available. Opacity measurements require highly accurate measurements of

density and temperature. At the National Ignition Facility (NIF), these experiments rely on x-ray imaging to estimate the density, and spectrometers to measure the temperature. Recent results show that the spectrometer is limiting the range in which they can capture data, and a new spectrometer design is needed to push the boundaries into needed measurement regimes [4, 5].

Turbulence is another regime in which scaling is important. For many years it was questioned that a high energy density regime, like an Inertial Confinement Fusion (ICF) capsule, could reach a turbulent regime. Experiments from the *Shear* campaign suggest that this is the case. The difficulty in these experiments is that turbulence requires spatiotemporal measurements of density and velocity *fluctuations*. Currently, High Energy Density (HED) experiments are limited to line integrated density measurements and are not capable of measuring velocity. Our physics codes are validated using measurements from traditional fluid experiments, such as in a shock tube, where experiments are able to capture spatially resolved density and velocity measurements on increasingly short timescales.

Recent work on ejecta experiments at the Special Technologies Laboratory (STL) have pushed the boundary of the velocity diagnostics into a higher energy regime. With similar facilities available via the Dual-Axis Radiographic Hydrodynamic Test Facility (DARHT) and Proton Radiography (pRAD), it should be possible to expand this capability into high-energy experiments. In the longer term, ways to measure velocity on ICF-like experiments are needed, and these initial experiments may provide a stepping stone to such a method. Another option is to carefully design a series of scaled experiments from our low-energy shock tube experiments, to high-order experiments at DARHT or pRAD, and then a high-energy experiment at OMEGA or NIF. Methods could be developed to compare the different data types, and work could be done to ascertain the effectiveness of scaling.

## ICF/MFE

The Thermonuclear Plasma group (P-4), makes specialized, state of the art measurements to advance our understanding of both inertial confinement fusion (ICF) and magnetic fusion energy (MFE) fusion plasmas [6]. We perform experiments while bringing our plasma diagnostics to bear around the lab, the nation, and the world. Our measurement techniques and advanced diagnostics not only enable our science but also cross over into the arena of test readiness. For example, gated x-ray imagers, gamma-ray based fusion burn time, and neutron imaging diagnostic systems for NIF at LLNL, and OMEGA at Rochester, and the Z-machine at Sandia, have been developed and deployed from LANL. We use these systems to gather information to diagnose fusion implosions in both indirect and direct drive configurations, on both laser-driven and magnetically driven pulsed power platforms. We even export our custom developed systems to European partners. For magnetic fusion experiments, we also make soft x-ray, vacuum ultra-violet, neutron, and infrared diagnostic systems for DOE Fusion Energy Sciences (FES) and ARPA-E experiments. As an example of the state-of-the art, we are

developing a unique laser inverse Compton scattering diagnostic to measure relativistic electrons during disruptions on the DIII-D tokamak at General Atomics in San Diego.

## QCD

Quantum Chromodynamics (QCD) is the theory that describes visible matter at the basic level of quarks and gluons (partons). One area of QCD involves the dynamics of quarks and gluons inside nucleon/nuclei, and can only be constrained by experimental measurements. The dynamics of quarks and gluons will change under different conditions such as in the high-pressure high-temperature Quark Gluon Plasma or a colder but dense nuclear medium. A series of new discoveries will be explored in these QCD experimental studies. The physics of the Quark Gluon Plasma has potential connections with the other plasma physics and the experimental detector development work can potentially be applied to other fields including experimental material science. LANL is well recognized as world-class experts in high energy nuclear physics with four decades of involvement in major experiments at FNAL, BNL and CERN. In the past 15 years, LANL has led novel detector technology developments in high energy experiments including the Relativistic Heavy Ion Collider (RHIC) PHENIX and sPHENIX experiments. The future Electron Ion Collider (EIC) and the Large Hadron Collider (LHC) provide new opportunities to explore several fundamental questions such as how visible matter is formed, what is the matter mass origin and what is the structure of exotic states with better precision measurements in a broader kinematic region [1,7]. The ongoing EIC Forward Silicon Tracker detector developments (LANL DR support, and anticipated future DOE funding) will establish LANL's leadership role in the EIC project which is listed as the highest priority of DOE nuclear physics office supported new facilities [1]. LANL is recommended to co-lead the heavy ion research program in the LHCb experiment at LHC supported by DOE Early Career funding. These basic science programs will not only position LANL as the pioneer in the QCD frontier fields within the upcoming 2-20 years, but also attract more talents and cultivate future leaders for this science. Cutting edge detector technology development, understanding of nuclear and particle physics, and advanced data analysis algorithms including machine learning techniques used by the high energy experiments have potential applications to various applied physics fields. These bring connections between the QCD basic science research and the other LANL missions.

The above-noted opportunities represent a diverse set of science and sponsors. Furthermore, the opportunities are the combination of scientific need, technical maturity for solutions, and programmatic interest which all are time-dependent quantities. Therefore, we encourage the Division to use these opportunities as a starting point for conversation with relevant sponsors and facility directors to establish which are actionable.

## REFERENCES

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- [2] T. Bredeweg et al., "(U) Radiochemistry roadmap", LA-CP-11-01195 (2011)

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- [5] T. S. Perry et al., “Progress toward NIF opacity measurements”, *High Energy Density Physics* **35**, 100728 (2020)
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## **How do we create, diagnose, and understand weapons-relevant experiments and physical regimes?**

### **SUMMARY**

Physics Division will continue to support the Los Alamos National Laboratory Weapons Program actively and enthusiastically. Physics Division has identified four important weapons program needs over the next 15 years to which the Division can, and must, make substantial contributions for the Laboratory to meet its mission goals. The four areas are:

- **Direct Certification Support**
- **Material Qualification**
- **Model Development and Validation**
- **Uncertainty Quantification**

Physics Division has identified several core scientific focus areas that it must support, grow, and continuously improve to meet weapons program requirements. Physics Division will prioritize and foster investments in these five scientific areas. In all of the research that the division undertakes, the goal is to increase our understanding of the phenomena under investigation through in-depth scientific research and analysis.

- **Archiving and Reanalysis of Historical Data**
- **Direct Certification Support**
- **High Energy Density Regime and Thermonuclear Burn**
- **Hydrodynamic Experiments**
- **Nuclear, Atomic, and Material Properties**

This Strategic Plan also identifies cross-cutting methodologies that will enable several of the above research areas simultaneously. These are:

- **Leveraging and Improving LANL's Experimental Infrastructure**
- **Collaborating at External Experimental Facilities**
- **Diagnostic Development**
- **Image and Data Analysis**
- **Archiving and Communicating Research Results**

Best practices for collaborative research environments will be implemented, focusing on:

- **Increase Division presence in scope and approach discussions**
- **Improve communications with program at all stages**
- **Consistent improvement in execution**

The Division also pursues non-weapons-related research in fundamental science and diagnostic instrument development. These other endeavors serve to support the weapons mission by attracting and providing personnel, advancing scientific skills, and establishing common infrastructure and culture. The weapons science research discussed in this white paper is mutually supporting of these other Division missions.

The figure below provides a graphical summary of this Science Driver. P-Division should focus on the areas of weapons program need by prioritizing the research topic areas and cross-cutting capabilities listed, while improving relationships with customers, colleagues, and collaborators in the areas listed.



Figure 1. Approach to meeting areas of weapons program need.

## INTRODUCTION

This Strategic Plan addresses the question listed, the most programmatically-focused of the science driver focus areas. The other two are “how do we discover the fundamental foundations of the Universe and explain unknown physical phenomena?” and “advancing measurements to enable predictive science and discovery.”

LANL’s agenda lists critical outcomes in the area of excellence in nuclear security in the next 5-10 years to “design, produce, and certify current and future nuclear weapons and reduce global nuclear threats<sup>1</sup>.” Physics Division has had a long history of providing experimental tools to answer questions of national importance, from Manhattan era work, through all of nuclear testing, and now in the era of no nuclear testing. The Division must now continue to support and advance the physics of the Weapons Program at LANL by contributing to efforts which lead to that critical outcome. *Physics Division can best serve the nation by applying a scientific approach to identifying improvements in our weapons physics, designing and executing experiments that address that issue, then apply cutting-edge analysis techniques to the acquired data, and finally developing new models that better represent the dynamics of a nuclear weapon.* These activities must be done in close collaboration with Los Alamos colleagues in the design, theory, computational, production, and other experimental divisions at LANL.

Since the ending of nuclear testing, we can no longer experimentally reach all weapons conditions. Therefore, current strategies to certify weapons use a combination of experimental evidence and computer simulations. When this is the case, methodologies to approximate weapons conditions, such as scaling, take on much more importance and need to be rigorously established.

Another constraint of modern experimentation is the cadence of experimental science, which is significantly different than that of code development and design. In order to develop an effective experimental capability often requires long-term investment, and so we are best suited to meet the needs of the Weapons Program by ensuring flexibility and responsiveness in our experimental science. Physics Division must provide, sustain, and exercise capabilities that can quickly be deployed to answer future weapons questions, such as design issues and Significant Finding Investigations (SFIs), in a timely manner. Without this long-term investment and sustainment, LANL will be unable to meet these national security challenges.

To meet future LANL needs, Physics Division staff identified four broad areas of need by the Weapons Program over the next 10 – 15 years that Physics Division must fill. Recognizing existing capabilities and gaps in those areas, the Division identified 5 areas of research that need to be sustained and grown to meet the Program's needs. Important cross-cutting capabilities are then listed. Support, development, and wide-spread use of these capabilities within the Division will enable the Division to address the weapons program's needs in the future *at the greater level of rigor that will be required*. Finally, areas for improvement in engagement with program customers, colleagues and collaborators are given.

## WHAT ARE THE FUTURE NEEDS OF THE WEAPONS PROGRAM?

The Weapons Program at LANL has a variety of needs that Physics Division must help to meet with its knowledge, experimental expertise, facilities and tools. Our scientific expertise and infrastructure allow prompt response to critical issues in the current and future stockpile by quickly deploying experimental resources to resolve issues. Maintaining the ability to contribute requires experienced and trained personnel who are constantly exercising their skills in forefront research as well as the development and maintenance of current and new diagnostic instruments in order to best respond to requirements for new data. It is also recognized that strategic directions are also likely to change as new issues arise. The Laboratory and Physics Division must be agile and flexible to meet those new directions.

### *Current and Future Certification*

For legacy weapon designs, the tie to nuclear tests is a primary focus of the certification methodology, and that has been the mode of operation since 1992. For new weapons designs, however, the tie to specific tests is no longer possible, and a different focus is needed. Based on current Stockpile Stewardship Science methodologies, the following will remain important in the future, and P-Division must find its role within that framework in order for the Laboratory to succeed:

- **Reliance on modern code simulation results for confidence in weapon system performance**
- **Use of existing nuclear test and laboratory experiment data in combination with a common modeling framework.**
- **Use of non-nuclear testing and its data to provide unit validation of models in the codes.**

#### *Material Qualification*

As the stockpile evolves, new materials and processes are being assessed for their use in nuclear weapons. In some of these cases, the new materials will be replacing materials that are no longer available, or at the very least, they will be using different methods of production. Characterization and qualification of new materials and processes requires a variety of experiments to characterize their behavior through extensive pressure, temperature and strain rate regimes.

#### *Model Development and Validation*

Weapons multi-physics performance codes contain models of the physics and chemistry occurring in a nuclear weapon. Models that accurately and reliably predict important physics with a high degree of confidence are required. These computational models are developed and validated using experimental data. Physics Division performs a range of fundamental discovery experiments to aid in model development and more integrated validation tests of models via experiments and through the UGT archive.

Next-generation multi-physics codes will incorporate models with reduced uncertainties for equations of state (EOS), strength, failure, hydrodynamics, radiation hydrodynamics, radiation transport, neutron transport, and plasma physics, among others. Physics division can provide exploratory efforts that point toward the appropriate physics to include in the models, can help provide the large amount of data to calibrate and validate the models, and in some cases can contribute directly to development of the models.

#### *Uncertainty Quantification*

Uncertainty quantification plays a critical role in weapons certification. The uncertainties of the experimental data can indicate whether an individual model in the code is sufficient to describe the behavior, and the uncertainties of an assemblage of experimental data sets are propagated through the machinery of the performance code to establish an overall uncertainty on the performance. That uncertainty can impact the confidence in the weapon's behavior.

Physics Division must provide uncertainties on all data that is provided to the design community, and to provide uncertainties that are well-grounded. The Division staff must understand and explain the cause and effect of experimental uncertainties in the use of the acquired data and models based on the data. A deep understanding of the physical mechanisms involved is necessary to determine these uncertainties, how experimental design affects those uncertainties, and how they scale from one regime to another.

## WHAT RESEARCH MUST PHYSICS DIVISION PURSUE IN ORDER TO REMAIN RESPONSIVE TO THE PRESENT AND FUTURE NEEDS OF THE WEAPONS PROGRAM?

The highest priority research to be pursued by the Division to address the needs stated above, as determined by consensus during the development of this plan are now given. Even though these are the highest priority areas, they are not the only topics to be pursued. As stated above, the Division must also remain alert, agile, and responsive to newly prioritized needs of the weapons program.

### *Archiving and Reanalysis of Historical Data (UGT) and Current Experiments*

Physics Division is the steward of the historical US nuclear test data covers many decades of above ground and underground nuclear tests, up until the final US nuclear test in 1992. *The information within the historical nuclear experiment database is unique and will never be replicated.* The Division also has a large amount of experimental data acquired from above-ground experiments relevant to certification model validation, uncertainty quantification, and material properties that should be analyzed and results made know to the certification and simulation communities.

All of these data can improve our predictive simulation capabilities and contribute to the uncertainty quantification (UQ) component of LANL's certification mission. The legacy data need to be archived effectively, in a way and a place that the XTD/XCP users can access through the Common Modelling Framework (CMF). Each kind of data need to have available analysts who understand the data in depth and can reanalyze the data as appropriate to meet certification needs. Having analysts who can also use the XTD/XCP performance codes and can observe the certification and UQ process is needed. The data need to be studied to produce the best and most broadly applicable UQ results that are then communicated to the customers. Most importantly, this extensive data set should be used to identify physics gaps and motivate new experimental research initiated by Physics Division that will allow better understanding of the recorded data and will improve models and their implementation in codes.

### *Direct Certification Support*

Physics Division should be more directly involved in the development of new certification strategic paths, should propose and lead new experiments, and should develop new diagnostic instruments to enable these experiments that meet future, more rigorous precision and uncertainty requirements. The Division should continue to support hydro experiments at DAHT, pRad experiments at LANSCE, and subcritical experiments at U1a, and should develop a framework with colleague organizations of the roles of each at these facilities. Developing effective experiments that reduce our uncertainty or increase our understanding of where uncertainties lie should be the goal of Physics' certification experiments. The division should also pursue more effective relationships with customers, collaborators and colleagues, as detailed later in this document.

### *HED Regime and Thermonuclear Burn*

The High Energy Density (HED) physics regime is one where radiation begins to play a major role and thermonuclear (TN) burning of fusion fuel is possible. Materials are usually in the

plasma state and behave differently than in other regimes. Such “hot physics” conditions place difficult constraints on our integrated codes and the models the codes use. Many aspects of HED behavior need improved models.

The current national HED facilities can provide experimental answers to guide development of many of those models. A vigorous program of experimentation should be pursued to target specific physics areas, to develop models and to then test those models. HED experiments, particularly with the smaller facilities, have the potential to generate significant amounts of data to quantify uncertainties, and this functionality should be utilized. Diagnostics to directly diagnose and quantifiably measure needed phenomena for comparison with the multi-physics codes need to be developed and nurtured (such as the technology for better resolved X-ray and simultaneous neutron radiographs of objects using short-pulse lasers), and the staff appropriate to opportunities available need to be recruited and trained.

Very large amounts of TN energy could be produced by the next generation of HED facilities currently envisioned by the Weapons Complex. LANL must continue active and energetic research in TN burn to provide credible and effective peer review to NNSA of the future facilities.

#### *Hydrodynamic Experiments Leading to Code Improvement*

Hydrodynamic experiments in both the low- and high-energy density regimes are used to develop and calibrate models, validate scaling arguments, and provide data for refinement of mix and hydrodynamic models. A particular area of interest is non-equilibrium flows. Understanding transitional flows and how to model them if they do not obey the assumptions of current models is important. This can be informed by experimental data that can measure variance from equilibrium and other modeling assumptions. Discovery experiments can drive the implementation of new physics into models via validation. The Division spans user facilities and regimes from traditional fluid experiments on small scale shock tubes at low energy densities to larger facilities like pRad, DARHT, the NIF and Omega at many times solid density and extreme temperatures. Improving the diagnostics in the higher energy density regimes should be a priority.

#### *Nuclear, Atomic, and Material Properties*

Properties intrinsic to an element or compound are important to LANL in order to simulate properly the response of a system to internal and external forces. Because not all materials can be measured in all physical regimes, theories and models are often used at LANL to calculate behavior where there are measurement gaps. Experimental measurements are required to guide the development of these models and to validate the models. Without proper comparison with data, the models generally carry large uncertainty. It is especially important to test models outside the range of expected operating conditions – these “long-lever-arm” measurements can often discriminate among models that give similar results in expected parameter spaces. Properties include, but are not limited to, opacities, equations of state, nuclear cross sections, material strength, and the response of materials to dynamic loading. Such measurements are often made at LANSCE, small-scale facilities, High-Energy-Density Facilities, and mined from the nuclear test archive.

Physics Division should be a major stakeholder in the design of these experiments and in the data analysis through deep comprehension of the data produced by diagnostic instrumentation so that justifiable data uncertainties can be provided. This knowledge will also help guide design and analysis of future dynamic experiments.

#### HOW DOES P-DIVISION MAINTAIN LEADERSHIP IN ESSENTIAL AREAS OF INTEREST THAT SUPPORT THE CONCEPTUALIZATION, EXECUTION, AND DIAGNOSIS OF WEAPONS-RELEVANT EXPERIMENTS?

Executing the research that maintains P-Division leadership requires targeted investment of time and effort into the enhancement of key capabilities. *These capabilities should be developed in conjunction with experimental campaigns, not in isolation, and the knowledge and tools developed should be propagated to the rest of the Division.* The following topical areas of P-Division's existing expertise and emerging leadership constitute a foundation for supporting LANL's weapons research mission.

##### *Advanced Analysis*

Increasingly powerful computer architectures and modern statistical techniques are being combined to draw ever more information from data, and P-Division will lead in adopting these techniques for the very unique task of certifying the Nation's stockpile. Particularly exciting opportunities lie in the areas of quantitative inference, uncertainty quantification, data synthesis and experimental design.

Through the initiative of P-Division staff, advanced methods of image analysis have been adopted into the weapons research performed at LANL. Long the home of Bayesian tools for analysis of radiographic images, P-Division is now becoming a resource for Machine Learning and other advanced approaches to image processing and quantitative inference. These methods are applied to image data collected across the complex, from DARHT to the NIF to Sandia's Z-machine, as well as U1a, and developed for imaging of neutrons, gammas and protons over a broad range of spatial and temporal scales. They serve to analyze noise, blur, distortion and artifacts so as to characterize physical systems with unprecedented confidence. Broadly speaking, areas of active research can be described by the following topics:

- **Synthetic modeling of experiments and diagnostics**
- **Synthesis of available multi-messenger measurements and simulations**
- **Statistical analysis of uncertainties in executed experiments**
- **Extrapolation of uncertainties to nearby regimes**

As recognized experts in diagnostic development and data collection, P-Division researchers will need to continue to lead in the development of advanced analysis tools that integrate expert-level descriptions of the experiments and instruments used with the most modern statistical methods and emerging computing platforms. This work represents a highly strategic pairing of a well-established identity in experimental design and execution with new internal and external collaborations in statistics and computing.

### *Advanced Diagnostics*

The development and deployment of advanced diagnostic techniques has long been a celebrated strength of P-Division. The recruitment, development and retention of talented diagnosticians and technologists underpins experimental capabilities essential to accomplishing LANL's mission. It remains essential to lead in this area by continually improving the quality of well-established measurement techniques through adoption of new and emerging technologies. It is equally important to continue leading innovation in measurement science by developing entirely new techniques with the project choices chosen by careful examination of the scientific issue being investigated. That is, the instrumentation development must be driven by the scientific questions being asked. Exploratory experiments, often primarily serving the purpose of proving new measurement techniques, are a defining activity performed by P-Division researchers. Furthermore, P-Division staff participate as both principal investigators and collaborators in the material science and engineering research that is fundamental to ground-up development of new instrumentation; a holistic approach to advanced diagnostic development includes all aspects of the technological lifespan from materials through devices to applications and data analysis.

### *Archiving and Communicating*

As stewards of the underground test data archive, P-Division plays an indispensable role in weapons certification by connecting the current world of advanced simulation to the bygone world of live testing. P-Division's success in archiving this data and developing products from it that serve the certification process are testament to the skill and expertise of P-Division personnel and will remain indispensable for the foreseeable future. Challenges of the coming years include integrating these analyses workflows with other advanced analysis techniques that are currently being developed and making more concrete connections to contemporary non-nuclear and sub-critical experiments. This involves not only applying new analysis to archival data, but also recognizing the value of persistent documentation as a living practice by applying an archival mindset to contemporary experiments. P-Division will expand the adoption of formal data management systems, interfacing with the Common Modeling Framework (CMF), and establish continuity between live tests and today's data to serve current and future generations of LANL's weapons program. The results of all experiments conducted by Physics Division must be documented through peer-reviewed publications and internal technical reports, both classified and unclassified.

### *Collaborative Engagement at External Facilities*

The sheer breadth of topics that must be addressed in the certification process dictates a commitment to shared outcomes across the complex. P-Division will not only have access to, but play a defining role in execution of the certification mission across DOE's cutting-edge facilities in both executive and advisory roles. Physics Division must take the lead in forming g collaborations across the Laboratory in order to meet the objectives of our research.

Establishing research teams with external collaborators may require participation in research projects that are removed from weapons problems, but still bear on the fundamental science under investigation. These teams will help showcase LANL credibility to the greater academic

community and often serve to increase the scientist pipeline to Physics Division. This type of research also helps support the national deterrent.

In particular, the development of Enhanced Capabilities for Sub-critical Experiments (ECSE) via the ASD-Scorpius project presents new opportunities for P-Division to maintain leadership in weapons-relevant research. Increased engagement with the project throughout the ongoing design phase, as well as during the transition to an operational phase, will solidify P-Division's role for the future of the sub-critical experiment field. P-Division needs to work with the program to ensure that there is a continued role in U1a experiments for all current and future platforms in Nevada.

#### *Utilization of LANL's World-Class Experimental Infrastructure*

Experimental facilities at LANL both create and probe weapons-relevant physics regimes. P-Division staff are highly respected for their expert stewardship of LANSCE capabilities and are uniquely poised to enhance the conditions generated and the diagnostics used to probe materials and configurations that are ever-more relevant to the needs of certification efforts. The development of capabilities to explore the hydrodynamic properties of Pu with proton radiography (Pu@pRad) and diagnose sub-critical neutron yields from integrated experiments are just two examples of potentially high-reward investments that serve to bolster P-Division leadership in experimental weapons research. Lujan, WNR, pRad, and DARHT are all leading facilities in their fields that have significant involvement from P-Division staff.

In order to work effectively in the areas listed, P-Division needs to continue to make the most of the available experimental infrastructure. The Division needs to have staff involved in planning of new operational modes or new experimental capabilities at these facilities in order to allow innovation in experimental avenues to meet weapons program objectives.

#### HOW DO WE STRENGTHEN AND GROW OUR RELATIONSHIPS WITH SPONSORS, COLLABORATORS ACROSS THE LABORATORY, AND COLLEAGUES ACROSS THE COMPLEX, FOR THE BENEFIT OF BOTH THE WEAPONS PROGRAM AND THE DIVISION?

This portion of the strategic plan focuses on the interactions of P-Division with the larger Weapons Program. We believe that an important concept to introduce here is that of a data or experiment cycle. The experiment cycle includes the initial determination of what data/information is needed, what solution or experiment will be used to acquire it, execution and analysis steps, transfer of data to the customer, documentation and presentation of the results, and determining whether further work is needed.

There are many steps in the cycle. However, many of the improvements to make with regards to strengthening relationships with customers, colleagues and collaborators are directly related to steps in that cycle and can be distilled into three common themes. The first is the need to strive for constant improvement of execution. The second is that Division staff need to be involved earlier and more directly in the initial scope and planning activities. Finally, the Division needs to be more effective in broadly communicating progress, results, and future capabilities. Giving Division staff experience interacting with customer organizations prepares

them for future project/program positions on a number of levels, for example. And, while not specifically called out in a step of the cycle, collaborative engagement in the synthesis of experimental data, theory and simulation is an important aspect.

Specific action items were developed for these areas, with timing/priority, that are separately available in a more detailed version of this section of the document.<sup>3</sup>

## REFERENCES

- [1] 2021 Los Alamos National Laboratory Agenda, available interactively at <https://www.lanl.gov/lab-agenda/index.shtml> or a printable version at the following address: [https://www.lanl.gov/lab-agenda/\\_assets/docs/Agenda-2021\\_LA-UR-21-20301.pdf](https://www.lanl.gov/lab-agenda/_assets/docs/Agenda-2021_LA-UR-21-20301.pdf)
- [2] Nuclear Posture Review Report. Washington, DC: U.S. Dept. of Defense, 2018. <https://www.hsdl.org/?view&did=807875>
- [3] Weapons Focused Science Driver White Paper, Maria Rightley, Steven Batha, Benjamin Tobias, William Buttler, Devin Connolly, Dana Duke, Verena Geppert-Kleinrath, Michael Ham, Scott Hsu, Anna Llobet, Eric Loomis, Yong Ho Kim, Marc Klasky, Jacqueline Mirabal-Martinez, David Montgomery, Patrick Younk, LA-UR-21-24262, available electronically from Maria.
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